Stellar Coronae in the Chandra and XMM-Newton Era
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Multiwavelength Aspects of Stellar Coronae

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Abstract. Coronae express different facets of their energy release processes in different wavelength regions. While soft X-ray and EUV emission dominates the radiative losses of the thermal plasma, hard X-ray emission (>10 keV) can be produced from non-thermal high-energy particles accelerated as a consequence of flare processes, and radio emission is often emitted from mildly relativistic electrons trapped in magnetic fields. Combined measurements of all emissions are important to understand the ultimate mechanisms responsible for coronal energy release and heating. This presentation will summarize a number of aspects for which multi-wavelength studies are important, both for quiescent and flare emission.

1. Introduction

It has become practice to think of stellar coronae as - perhaps more luminous - equivalents to the wonderfully (and colorfully) shining outer *solar* atmosphere on Skylab, Yohkoh, SoHO, and TRACE images. The vast progress in the areas of solar EUV and X-ray astronomy, in particular of imaging, and the immense flood of *stellar* data from a completely new X-ray discipline - that of high-resolution stellar coronal X-ray spectroscopy from *XMM-Newton* and *Chandra* - more than justifies a place of honor for this view. But don't we miss a point? Do soft X-rays provide a self-contained description of a stellar corona, of its energetics, of its structure, of the physics at work, of the essentials that make up 'the corona'?

The present review tries to illuminate aspects of stellar coronal physics from alternative angles, in particular related to non-thermal phenomena and their relation to the soft X-ray radiating plasma. The main goal is to provide contrasting and complementary points to a conference largely devoted to new X-ray results. The theme focuses on the important role that high-energy processes play in a corona - invisible to X-ray detectors, often occurring before the appearance of X-ray signatures, but very relevant to the 'big picture' of what the term 'corona' really stands for.

2. Why Multi-Wavelength Coronae?

During flaring episodes, the solar corona becomes a truly multi-wavelength object. Often before any significant soft X-ray brightening occurs, tangled magnetic fields produce immense numbers of high-energy particles up to relativistic energies. Evidence for non-thermal particles is ubiquitous; each solar flare

seems to produce them, in a wide variety (deka-keV electrons, relativistic electrons, high-energy ions, high-energy neutrons, pions), and they contain a significant fraction of the total energy released in a flare (Hudson & Ryan 1995). If their power-law distribution in energy is not rigidly cut off toward lower ($\sim 10-20$ keV) energies, embarrassingly large total energies could be contained in this population (Dennis 1988). The production of high-energy particles is an efficient way to release energy built up in non-potential magnetic fields in tenuous plasma environments, and they are efficient agents to transport this energy to different locations in very short times. Upon collisions in denser environments, they produce hard X-rays (> 10 keV) and γ rays. Mildly relativistic electrons trapped in magnetic fields emit radio gyrosynchrotron emission. The short time scales involved (seconds, compared to minutes for soft X-ray plasma) are ideal tracers of processes occuring at the time of the initial energy release.

It was an unanticipated but momentous discovery that magnetically active stars are quasi-steady emitters of *non-thermal* gyrosynchrotron emission (e.g., review by Dulk 1985). It testifies to the presence of a large number of relativistic electrons in stellar coronae. How are they accelerated, and where does this particle population carry its energy to? The wide-ranging analogy with solar flares provokes further questions: i) Is there also a stellar non-thermal hard X-ray component? ii) Are the high-energy particles responsible for coronal heating? iii) Is the apparently quiescent emission made up of flares?

Non-thermal *stellar* hard X-ray emission has not yet been detected given the instrumental limitations. But thanks to detailed studies at radio wavelengths, the initial phase of stellar flares and energy release can be studied, with potential implications for our understanding of coronal heating, and *spatially resolved* images of stellar coronae (only one aspect of them, alas!) can be taken.

3. Coronal Structure

The spatial structure of non-thermal coronae is routinely accessible to Very Long Baseline Interferometry (VLBI) at milliarcsec scales (Table 1). It was soon recognized that RS CVn and Algol-type binaries are surrounded by large, global-scale non-thermal coronae (Mutel et al. 1985), often composed of a compact core plus an extended halo. The former is thought to relate to initial phases of flares, while the latter contains slowly decaying high-energy particles injected from the flare site.

Similar spatially-resolved observations have been obtained from T Tau stars (Phillips, Lonsdale, & Feigelson 1991) and magnetic chemically peculiar Bp/Ap stars (Phillips & Lestrade 1988, André et al. 1991). The have mostly been interpreted in terms of global, dipole-like magnetic fields surrounding the active star(s) on spatial scales exceeding the stellar size by far. In the most elaborate models, the magnetic fields are compressed (e.g., by a weak stellar wind escaping at high latitudes) toward the equatorial plane where they build up current sheets that accelerate electrons. These are trapped within the magnetospheres, somewhat similar to the Earth's van Allen belts (Drake et al. 1987, André et al. 1988, Morris, Mutel & Su 1990, Linsky, Drake, & Bastian 1992).

VLBI techniques have been much more demanding for single late-type dwarf stars, both due to lower flux levels and (supposedly) smaller coronal sizes. Some

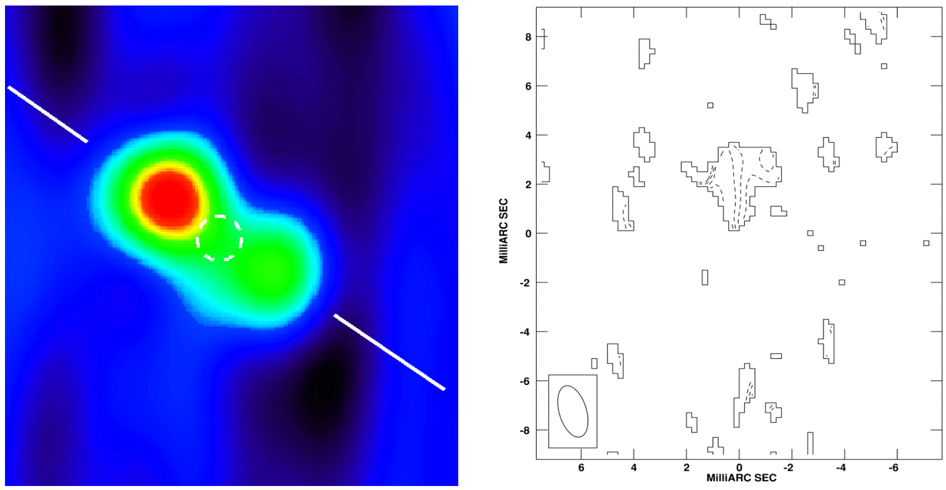

Figure 1. **Left:** The dMe star UV Cet B as seen at radio wavelengths by the VLBA. The separation between the two components is about 1.4 mas, while the best angular resolution is 0.7 mas. The circle indicates the photospheric diameter of UV Cet B, and the solid line marks the putative rotation axis - assumed to be parallel to the axis of the visual-binary orbit (after Benz et al. 1998). - **Right:** Radio polarization map of the spatially resolved RS CVn binary UX Ari. Note the gradient in the polarization contours across the stellar image (from Beasley & Güdel 2000).

observations with mas resolutions show unresolved (quiescent and flare) sources, thus providing stringent constraints on the radio brightness temperature ($T_b > 10^{10}$ K) and therefore on the (non-thermal) energies of the involved electrons (Benz & Alef 1991, Benz, Alef, & Güdel 1995), while others have shown evidence for extended coronae, such as for the eclipsing YY Gem, with coronal sizes up to several times the stellar size (Alef, Benz, & Güdel 1997, Pestalozzi et al. 1999).

The dMe star UV Cet B reveals a pair of giant synchrotron lobes (Figure 1), with sizes up to 2.4×10^{10} cm and separated by $4-5$ stellar radii along the putative rotation axis of the star, suggesting very extended magnetic structures above the magnetic poles (Benz, Conway, & Güdel 1998). An analysis of the synchrotron losses constrains the strength of extended magnetic fields to $15 - 130$ G. VLBA imaging and polarimetry of Algol reveals a similar picture (Mutel et al. 1998) with two oppositely polarized radio lobes separated perpendicularly to the orbital plane by more than a stellar diameter of the K star. Global polarization structure has been found in UX Ari, indicating the presence of large-scale ordered magnetic fields on size scales of the intrabinary distance (Beasley & Güdel 2000).

Some coronal structure information can also be derived from rotational modulation and eclipses. The imaged large-scale magnetospheric structures would suggest that this approach is less promising, and there are indeed not many clear-cut examples available. Some optically eclipsing systems such as YY Gem or AR Lac simply show no radio eclipses (Alef et al. 1997, Doiron & Mutel

Table 1. SELECTED VLBI RESULTS FOR ACTIVE STARS

Star	R_* [a] (cm)	R_c/R_* [b]	model[c]	Reference
RS CVn and Algol Binaries				
σ CrB	8.4×10^{10}	1.2		Mutel et al. 1985
HR 1099	2.7×10^{11}	1.6		Mutel et al. 1985
HR 5110	2.0×10^{11}	1.7		Mutel et al. 1985
UX Ari	3.3×10^{11}	3.6	halo	Mutel et al. 1985
UX Ari	3.3×10^{11}	<0.45	core	Mutel et al. 1985
Algol	2.4×10^{11}	2.5	halo	Lestrade et al. 1988
Algol	2.4×10^{11}	<0.5	core	Lestrade et al. 1988
Algol	2.4×10^{11}	1.4	polar lobes	Mutel et al. 1998
UX Ari	3.3×10^{11}	4.5	MS	Beasley & Güdel 2000
Pre-Main Sequence Stars				
HD 283447	2.1×10^{11}	12−15	MS	Phillips et al. 1991
HDE 283572	2.4×10^{11}	<14	MS	Phillips et al. 1991
Hubble 4	2.4×10^{11}	12−24	MS	Phillips et al. 1991
DoAr 21	2.4×10^{11}	10−12	MS	Phillips et al. 1991
Chemically Peculiar Stars				
ρ Oph S1	3.0×10^{11}	$6.4^{+1.2}_{-2.4}$	MS	André et al. 1991
σ Ori E	2.8×10^{11}	≤6	MS	Phillips & Lestrade 1988
Main-Sequence Stars				
AD Leo	2.0×10^{10}	<1.8		Pestalozzi et al. 1999
AD Leo	2.0×10^{10}	<1.9		Benz et al. 1995
AD Leo	2.0×10^{10}	<3.7		Benz et al. 1995
YZ CMi	2.4×10^{10}	1.7±0.3		Pestalozzi et al. 1999
YZ CMi	2.4×10^{10}	<1.7		Benz & Alef 1991
EQ Peg	1.3×10^{10}	<1		Benz et al. 1995
YY Gem	4.8×10^{10}	2.1±0.6		Alef et al. 1997
UV Cet	1.0×10^{10}	2.2−4	polar lobes	Benz et al. 1998

Notes: [a] Information used from Hipparcos Catalog (ESA 1997) and Strassmeier et al. 1993
[b] R_c = coronal radius, R_* = stellar photospheric radius.
[c] proposed geometric strucutre; MS = magnetospheric

1984), suggesting that the coronal structures are very large or completely outside the eclipse zone. Some light-curve modeling even suggests the presence of radio-emitting material between the binary components of such systems (Gunn et al. 1997, 1999).

Are these structures co-spatial with the X-ray coronae implied for these stars? Pressure balance for the hot thermal X-ray plasma would imply electron densities n_e less than a few times 10^8 cm^{-3} (Beasley & Güdel 2000); the requirement that the local plasma frequency $\nu_p = (n_e e^2/(\pi m_e))^{1/2}$ be less than the observing frequency (~1 GHz) restricts $n_e < 10^{10}$ cm^{-3}. Both values contra-

dict explicit X-ray density measurements (Güdel et al. 1999, 2001ab). The low densities are also not compatible with the rapid decay time scales usually seen in stellar X-ray flares. Further, the high-energy electrons in a termal-plasma environment thermalize on time-scales of $\tau = 1.6 \times 10^{12} E_{\mathrm{MeV}}/n_{\mathrm{e}} \approx 1 - 100$ s (for likely parameters; Benz & Gold 1971). Lastly, free-free absorption along the line of sight is $\propto n_{\mathrm{e}}^2 \ell$ with ℓ being the characteristic source depth - again, the opacity would suppress most of the emission. The deep X-ray eclipse of the YY Gem binary restricts the X-ray emitting plasma to intermediate and low latitudes and the scale height to $\leq 1R_*$ (Güdel et al. 2001a), at variance with the VLBI measurements. These arguments make it unlikely that the large radio structures are spatially related to the X-ray coronae.

4. Energy Release: Evidence from Solar Flares

Are radio and X-ray coronae linked energetically, in particular during flares? We first review some important evidence from the Sun. Solar flare hard X-ray emission correlates with microwave radiation both in peak flux and, to sub-second accuracy, in time (e.g., Kosugi, Dennis, & Kai 1988). Such correlations are now taken as evidence that both the $\sim$10$-$100 keV electrons responsible for hard X-rays and the higher-energy radio emitting electrons belong to one and the same non-thermal parent population.

A standard flare scenario devised from many solar observations proposes that accelerated coronal electrons precipitate into the chromosphere where they lose their kinetic energy by collisions, thereby heating the cool plasma to coronal flare temperatures. The subsequent overpressure drives the hot material into the coronal loops, giving rise to a soft X-ray flare. The radio gyrosynchrotron emission from the accelerated electrons is roughly proportional to the instantaneous number of particles and therefore to the power injected into the system. On the other hand, the X-ray luminosity is roughly proportional to the total energy accumulated in the hot plasma. One thus expects, to first order,

$$L_R(t) \propto \frac{d}{dt} L_{\mathrm{X}}(t) \tag{1}$$

which is known as the "Neupert Effect" (Neupert 1968) and has been well observed on the Sun in most impulsive and many gradual flares (Dennis & Zarro 1993). Further evidence for the operation of the chromospheric evaporation scenario include:

- Footpoint brightening of distant ($\sim 10^9$ cm) loop footpoints within a fraction of a second, involving non-thermal speeds for the energy transport (Sako 1994, Hudson & Ryan 1995);

- Prompt soft X-ray footpoint brightening together with hard X-rays, while the bulk volume of the extended loop follows later, according to equation (1) (Hudson et al. 1994);

- Spatially related and temporally correlated evolution of soft X-ray, hard X-ray, and radio structures (Nishio et al. 1997);

- Correlated hard X-ray and white light emission, both as a consequence of impacting fast electrons (Hudson et al. 1992);
- Blueshifted Ca XIX enhancements that are closely correlated with hard X-rays, signifying the rapidly developing upflows during the impact episode (Bentley et al. 1994).

5. Energy Release and Radio Flares in Stars

The search for stellar equivalents to the solar Neupert effect has been a story of contradictions if not desperation. A first breakthrough came with the simultaneous EUV (a proxy for X-rays) and optical observations (a proxy for the radio emission) of a flare on AD Leo (Hawley et al. 1995) and radio + X-ray observations of several flares on UV Cet (Güdel et al. 1996). The relative timing between the radio bursts and the gradual X-ray flares was found to be similar to solar equivalents (Figure 2a), including the energy ratios seen in non-thermal and thermal emissions. These observations gave conclusive evidence that the production of high-energy particles accompanies flare coronal heating, and may actually be the cause for the heating itself through chromospheric evaporation.

Given the large size of RS CVn radio magnetospheres, are there similar physical mechanisms at work in such coronae as well? It is conceivable that radio-emitting particles are more detached from the heating site and may not be responsible for chromospheric evaporation. A recent observation with *XMM-Newton* and the VLA seems to indicate otherwise. Figure 2b shows, from top to bottom, the X-ray light curve, its time derivative, and the radio light curve during a large flare episode on the RS CVn binary σ Gem. We concentrate on the second flare that is fully visible at radio wavelengths, i.e., between 1.02$-$1.32 d. The radio and X-ray derivative curves correlate very well in time, with no significant relative time delay. Evidently, the release of high-energy particles is closely coupled with the heating mechanism. Correlated behavior does, however, not prove the operation of chromospheric evaporation as both mechanisms may be unrelated consequences of the energy release process. A necessary condition is that the energetic particles carry enough kinetic energy to explain the released soft X-ray energy. Under simplified assumptions such as an electron power-law distribution in energy, a reasonable lower energy cutoff around 10 keV, and the absence of strong changes in the radio optical depth, an order of magnitude estimate of the total energy in the electrons results in $E_{\rm tot} = 10^{33} - 10^{36}$ erg (Güdel et al. 2001c). This estimate holds for a magnetic field strength B between 20$-$200 G and a power-law index $\delta = 2.0-3.5$, values that have previously been found from magnetospheric modeling, and an electron lifetime of $\sim$1500 s as inferred from the light curve (shorter lifetimes result in larger energies). The total released energy in the X-ray flare is estimated to be 4×10^{34} erg. The kinetic particle energy is thus sufficient to explain the heating for a broad range of parameters B, δ.

In retrospect, we find a similar timing between radio and X-ray flare events in some previously published light curves, although the Neupert effect was not discussed. Most evidently, radio emission peaking before the soft X-rays, thus suggesting the presence of a Neupert effect, can be seen in the examples presented

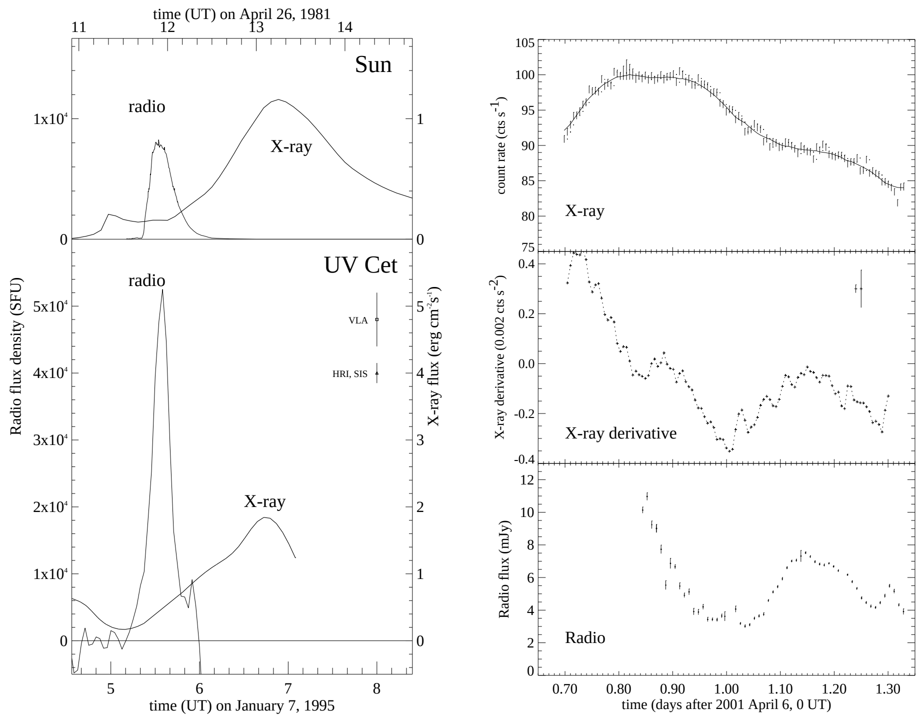

Figure 2. Neupert effect seen at radio and X-ray wavelengths. **Left**: Lower panel shows example on the dMe star UV Cet, and upper panel a similar solar case (from Güdel et al. 1996). **Right:** Example from RS CVn binary σ Gem. Top: X-ray light curve. Middle: Time derivative of X-rays. Bottom: Radio light curve (after Güdel et al. 2001c).

by Vilhu et al. (1988), Stern et al. (1992), and Brown et al. (1998). To conclude this section, it is important to note that the Neupert effect is neither observed in each solar flare (Dennis & Zarro 1993) nor in each stellar flare.

6. Energy Release and Coronal Heating in Stars: All Made of Flares?

The very high temperatures attained in non-flaring X-ray coronae of magnetically active stars have often been taken as a hint for the presence of (micro)-flaring. In such a model, both the quiescent radio and the quiescent X-ray emissions could be the consequence of many superimposed flares, predicting that the two emissions relate to each other the same way as they do in flares.

Figure 3 plots average loss rates in X-rays vs radio, for quiescent stars, for *solar* flares, and for three flares observed on UV Cet. Evidently, flares and quiescent emission follow the same trend (see Güdel & Benz 1993, Benz & Güdel 1994, Güdel et al. 1996). Is it conceivable that all of the quiescent emission is made up of flares?

Audard et al. (2000) statistically studied the flare energy distribution at EUV wavelengths to conclude the flares are distributed in energy according to

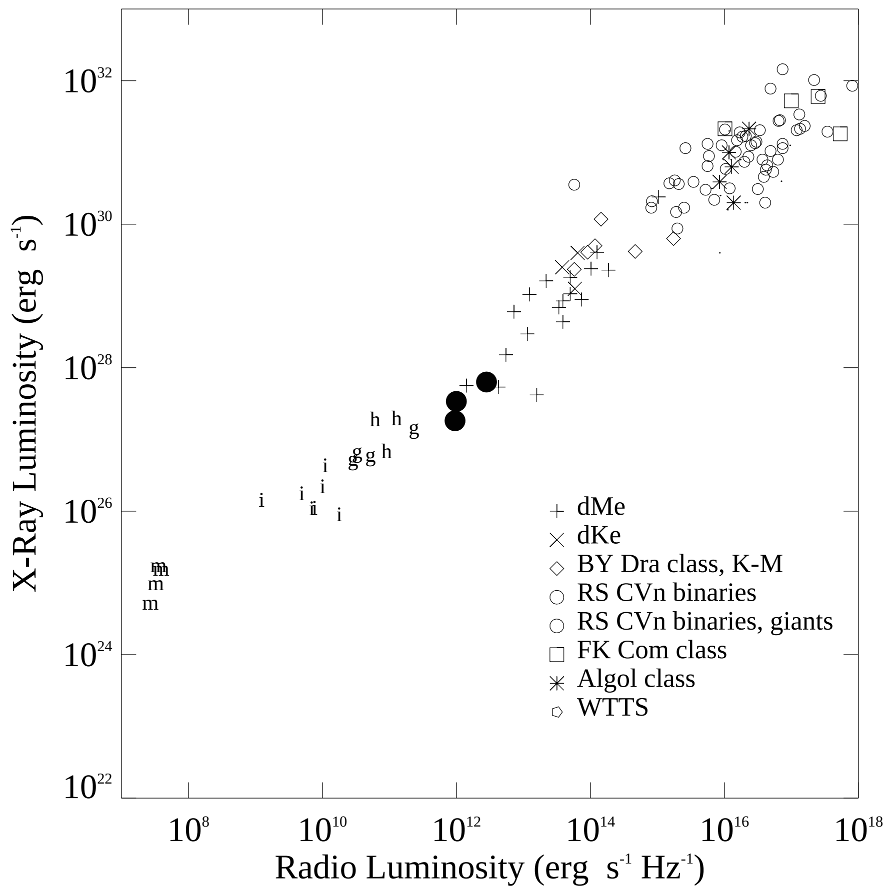

Figure 3. Correlation between X-ray and radio luminosities. Upper right half of diagram shows quiescent luminosities of various stellar classes by different symbols. Lower left part shows average radiative losses during a sample of *solar* flares (letters m, i, g, h); the three solid circles mark the loci of three flares on UV Cet for which the Neupert effect has been observed (average losses over flare durations after Benz & Güdel 1994 and Güdel et al. 1996).

a power-law, $dN/dE \propto E^{-\alpha}$ where $\alpha > 2$ is suggested. Similar results have been obtained by Güdel et al. (these proceedings) and Kashyap et al. (these proceedings) from a statistical investigation of a long monitoring of AD Leo. The following predictions should then be verified:

1) The rate of detected flares should increase with increasing quiescent luminosity (this is a necessary, but not sufficient condition for the flare heating hypothesis, see Audard et al. 2000);

2) The X-ray emission measure distribution should be compatible with that of a statistical distribution of rising and decaying flares;

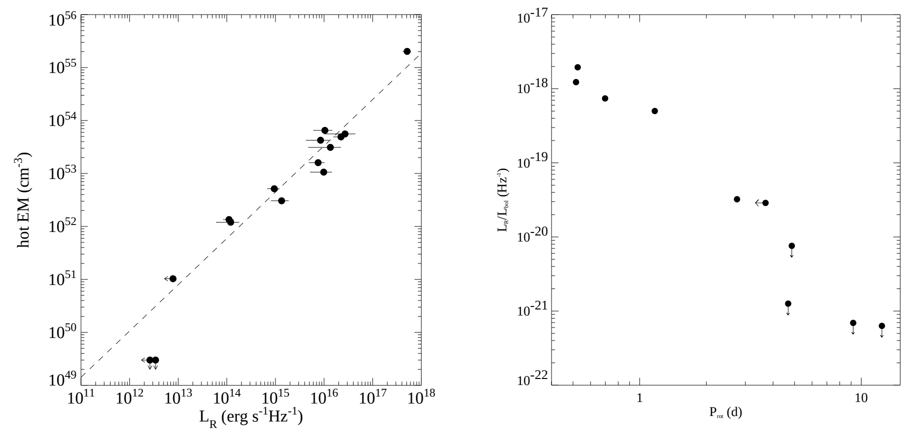

Figure 4. **Left:** Dependence between radio luminosity and hot coronal plasma. **Right:** Dependence of quiescent radio emission on rotation period for solar analogs. (Details and references: Güdel et al. 1998, Güdel & Gaidos 2001d.)

3) The radio emission should strongly be related to the *hot* plasma component of the X-ray emission measure distribution. More active stars should show both more radio emission and a hot tail in the EM distribution.

There is evidence for all three predictions to hold (Audard et al. 2000 for [1], Güdel 1997, Güdel, Guinan, & Skinner 1997, and Güdel et al. [these proceedings] for [2], and Güdel et al. 1997, 1998 for [3] - see below).

7. Particle Acceleration and Coronal Heating

If flares and non-thermal particle populations are ultimately responsible for coronal heating, one should see further evidence in the end-product - the hot plasma itself. Correlating the *hot* (> 10 MK) emission measure of active stars (as determined typically by low-resolution devices such as *ASCA*) with the overall quiescent radio luminosity indeed shows a tight correlation, see Figure 4a. The large range in both parameters involved is likely to be due to a large range in coronal volume (from coronae of solar analogs to giants), but the correlation can nevertheless not be reduced to a trivial consequence of geometric effects. It rather indicates that the presence of non-thermal particles specifically correlates with the presence of *hot* plasma. Note that this correlation breaks down for cooler, few-MK plasma: The Sun does not maintain any appreciable quiescent emission, nor does it show quiescent plasma above 10 MK.

The mutual dependence between accelerated particles and hot plasma is also visible as an evolutionary effect. Since the X-ray luminosity L_X of a given class of cool stars correlates with the average coronal temperature (Figure 5) and L_X decays with age, the coronal temperature decays with age as well (Güdel et al. 1997). The expected accompanying, rapid decay of the quiescent radio

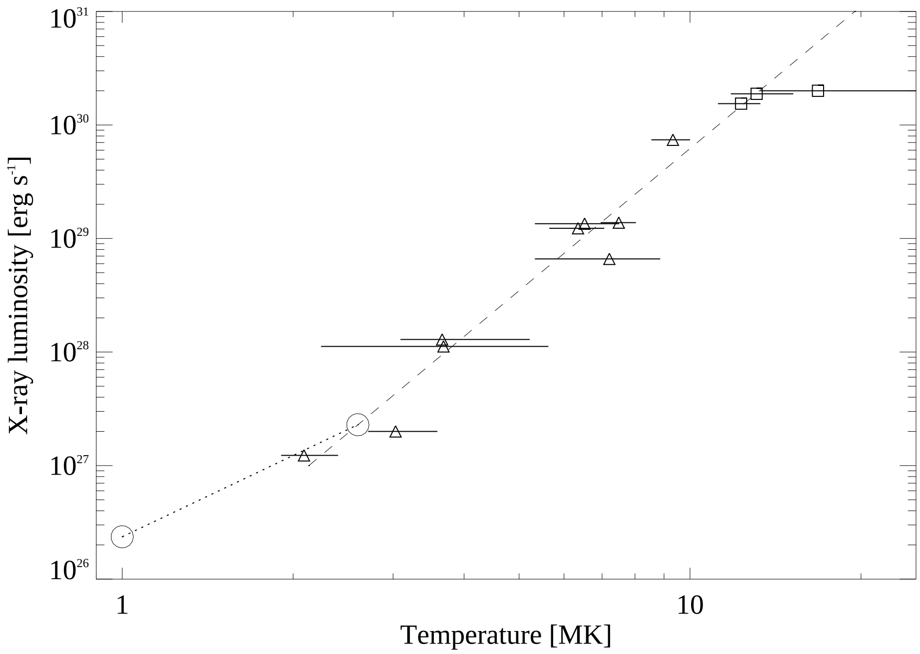

Figure 5. Dependence of average coronal temperature of solar analogs (sample from Güdel et al. 1997) on the overall X-ray luminosity. The circles give the range for the solar corona after Peres et al. 2000.

luminosity with increasing rotation period (thus, increasing age) is shown in Figure 4b for solar analogs.

8. Conclusions

Stellar coronae show many facets as soon as we open our view to a variety of wavelengths. Some high-energy processes cannot yet be studied on stars due to sensitivity limits. However, results at hand suggest a very intimate interplay between magnetic fields, high-energy processes of energy release, particle acceleration, and coronal heating both during flares and during quiescence:

- Non-thermal coronae show a bewildering variety of sizes and structures that can just be resolved with VLBI techniques. No solar analogy exists.
- Non-thermal stellar coronae are likely to be separate entities and are not co-spatial with soft X-ray coronae.
- A large amount of energy is available in accelerated particles during stellar flares. They may partly be responsible for coronal heating during flares via chromospheric evaporation as suggested by the presence of the Neupert effect.

- There is various evidence that quiescent stellar emission (both non-thermal and hot-thermal) is a consequence of superimposed flaring events.

Evidently, the study of the interplay between high-energy electrons and coronal heating is important. It may link quiescent coronae to flare physics, and may thus relate back to solar physics where detailed study of physical mechanisms is easier. A notable missing link are *hard X-rays* from stars. There is hope that future large-area devices such as *Integral* will remedy this situation.

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